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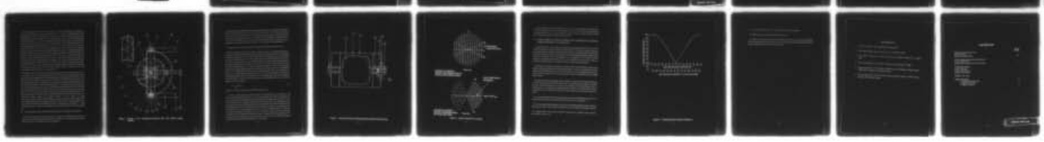

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TECHNICAL REPORT T-79-81

LEVEL II

GIMBAL PICKOFF TECHNOLOGICAL STUDIES

Aubrey Rodgers
Technology Laboratory

August 1979

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35809

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The purpose of this study and analysis is to employ more sophisticated gyro gimbal pickoff component technology to replace existing pickoff designs. The existing wide gyro pickoffs experience gimbal wiring and slipring torques, potentiometer wiper lift off during flight environment, noise, increased friction, and assembly cost. The goals of this study are to gain a better understanding of the pickoff error mechanism and to utilize the major advances in component development, materials, and manufacturing techniques as applicability to the design of inertial instruments.

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1. INTRODUCTION

The purpose of this study and analysis is to employ more sophisticated gyro gimbal pickoff component technology to replace existing pickoff designs. The existing wide angle gyro pickoffs experience gimbal wiring and slipring torques, potentiometer wiper lift off during flight environment, noise, increased friction, and assembly cost. The goals of this study are to gain a better understanding of the pickoff error mechanism and to utilize the major advances in component development, materials, and manufacturing techniques as applicability to the design of inertial instruments.

The purpose of the task is to study, analyze, and recommend a pickoff concept that will satisfy the following minimal requirements:

- Operate in an environmental range from 100 to 1500 g's.

- Mission time from 35 to 70 seconds.

- Fast reaction time less than 100 ms to minimize user's exposure time and allow maximum rate of fire.

- Wide angle gyro mechanical degree-of-freedom and pickoff range from ±45 to ±65 degrees.

- Small volume and light weight for projectile or missile diameter size less than 155 mm O.D.

- Cost effectiveness as an equal parameter with performance, a major criterion for the subsequent technological concept studies.

The objective of this task is to fulfill the concept requirements and potentially replace existing gyro designs that are used in high velocity, small missile systems for the 1980-90 time frame.

2. GIMBAL PICKOFF COMPONENT TECHNOLOGICAL STUDIES

A. RADIANT ENERGY SOURCES

The performance, reliability, linearity and threshold current of laser diodes have improved substantially in recent years. It is now possible to produce a laser diode with a threshold current

that emits a minimum of five milliwatts of power with a predicted lifetime of over 10 years of operation.

These characteristics make it clear that laser diodes will be a dominant radiant energy source in future fiber optic designs. Quantity demand will allow production of laser diodes at cost, consistent with those of current semi-conductor components.

Temperature is a critical environment that affects the reliability of laser diodes. To minimize this effect, a heat-sink material is deposited on the laser chip. The heat generated inside the diode is dissipated immediately into the large area of high thermal conductivity for efficient heat extraction.

Laser threshold current is typically about 100-300 milliamperes, its rise time of radiant flux is about 10 picoseconds, the operating temperature is from 0 to 65° C and the storage temperature is from -196 to +140° C. The source is usually mounted in a hermetic TO-5 package.

Gallium-arsenide (GaAs) or gallium-aluminum-arsenide (GaAlAs) laser diodes emit radiant energy at fixed wavelengths at 800 to 900 nanometers. The laser diodes emit incoherent radiation when electrically energized with low power.

As the input power increases, a threshold is reached above which the diode begins to emit coherent radiation. Above the threshold, the optical bandwidth becomes narrower than for incoherent light, and the coherent light increases sharply as a function of power. Combining laser diodes increases intensity, but only at higher cost and with lower beam quality than for a single laser diode.

A typical laser diode that emits 5-milliwatts of continuous radiant energy at 850 nanometers can produce a relatively narrow beam spread, ±5 degrees, in one parallel plane. This narrow output beam produces a well-defined radiometric centroid when reflected by the gyro rotor surface and intercepted by the detector.

Laser diodes can launch considerably more power into a fiber optic bundle, but are more costly and require more complex drive circuitry than light emitting diodes (LED).

A good radiant source for fiber optics is a small, bright, fast, monochromatic and reliable unit. A small energy source is efficient. High radiance assures that plenty of radiation gets coupled into the fiber optics. A narrow spectral line width helps keep the dispersion in the fiber low. And, of course, the radiation source must have a lifetime of thousands of hours.

Laser diodes and LEDs are now being developed with factory assembled fiber pigtails attached to avoid the need for alignment of fiber to devices smaller than a grain of sand. Only a simple source-fiber-sensor interface is required. The LED, a dependable solid state device, is capable of transmitting moderate optical power at modulation rates in the tens of megahertz.

B. FIBER OPTICS

Fiber optics is based on the ability of smooth strands of transparent materials to conduct radiant energy with high efficiency. The radiant energy conducted by a fiber is reflected from the walls by total internal reflection made virtually lossless by coating or cladding the walls with a transparent layer of material having a lower refractive index than that of the fiber. The cladding protects the fiber interface from scratches and dust and also prevents leakage of radiant energy.

Optical fibers are made of glass, optical plastics, or fused silica. Glass fibers are used in applications requiring radiant energy transfer either in flexible bundles or in rigid fiber optic face plates. (A face plate is made from a large number of short fibers aligned side by side and fused together to form a solid plate. This type is used to transmit coherent radiant energy images that can be viewed under bright, direct light). Plastic fibers are used in low-cost illumination applications. Fused silica fibers are used as low-loss transmission lines.

Bundles of fibers without any systematic alignment of the individual fiber ends, called *light wave guides*, are used to transmit radiant energy along flexible paths for various distances depending on the attenuation properties of the fibers. A wave guide that consists of cladded fibers grouped together is known as a non-coherent bundle and probably is the most widely used of all fiber optic components. The diameter of the individual fibers varies from approximately 50 to 200 micrometers. The bundle is very flexible, with minimum bending radius determined by the protective cladding rather than the fibers. The term *step-index* is applied because the index of refraction of the core is constant with radius and is 1% to 5% greater than that of the cladding.

Because of the principle of total internal reflection, radiant energy is reflected at the core/cladding interface and thus guided through the fiber. Common types are:

- Silica-cladding/silica-core (the lowest-loss, highest-bandwidth),

- Plastic-cladding/silica-core (suitable for moderate distance),

- Plastic-cladding/plastic-core (high loss). Special fuzed silica and modified silica optical fibers have attenuations as low as 2dB/km in the near infrared portion of the spectrum.

Attenuation in either type of fiber is caused by absorption principally due to impurities in the core material, and by scattering due to inhomogeneities and inclusions in the core. An important consideration in the manufacture of low-loss glass fibers is avoidance of water absorption as the glass is processed. In a modified doped-deposited-silica process, hydroxal-ion content is very low; the resulting attenuation is very low, typically 6dB/km at 850 nm or fused silica fiber having 20 to 100 dB/km.

If the fiber core is free of inclusions or defects which can cause radiation scattering and loss, it will display an intrinsic scattering caused by density fluctuations.

Attenuation of fiber optics is customarily expressed in decibels, and is usually normalized to one-kilometer reference length. Thus, from powers transmitted and received over a length of L kilometers,

$$\text{Attenuation} = \frac{10 \log_{10} \frac{P\ rec'd}{P\ trans}}{L} \text{ (dB/km)}. \tag{1}$$

Optical-power loss can be thought of in the same way as the ohmic loss of conventional wire, for which the linear resistance is known and the potential drop is easily calculated.

Attenuation of a particular fiber is a function of the transmitting source's optical wavelength. In comparing fiber specifications a designer should consider loss figures for a given wavelength, such as 850 nm.

A radiant energy pulse entering an optical waveguide undergoes an increase in bandwidth while traversing the length of the fiber. This is due to both material properties and the geometry of propagation, described mathematically as modes.

Bandwidth is limited by the broadening of pulses being transmitted through a given fiber. Such broadening occurs when different modes arrive at the sensor at different times. This model dispersion is due to the unequal mode velocities and obvious path-length differences in step-index fibers. Step-index fibers are those in which the index of refraction is constant in the fiber and has an abrupt "step" at the surface. Some fibers available are:

- Multi-step; having more than one abrupt change of index of refraction.

- Graded-index fiber, in which index of refraction varies in the fiber, usually decreasing approximately parabolically from the center to the surface. The parabolic refractive-index profile of a graded-index fiber greatly reduces such dispersion and, as a result, a graded-index fiber can have substantially greater bandwidth, usually several hundred megahertz for a 1 km reference length.

Another important optical parameter of interest is the numerical aperture. The numerical aperture (NA) is: a measure of the maximum acceptance angle for light propagation in the fiber; at angles larger than this, there is no longer total internal reflection.

$$NA = \sin \theta = \sqrt{n_1^2 - n_2^2} \tag{2}$$

where θ = one half of the input core angle.

n_1 = index of refraction of core.

n_2 = index of refraction of cladding.

This is the sine of the half-angle within which the fiber can accept or radiate energy. High numerical aperture implies greater coupling efficiency between the radiant source and fiber. Thus a high NA fiber can be used effectively with an inexpensive low-brightness LED. However, NA is a function of the core-to-cladding index difference. For this reason, an increase in NA usually is accompanied by higher attenuation and lower bandwidth.

In radiant energy wave guide applications, it is possible to modify the end configurations to any desired geometrical form. Alternatively, one bundle may be divided into several branches to provide several radiant energy outputs. In such arrangements, only the total area of the fiber bundle must be maintained at both ends of the system since the individual fibers are of uniform size.

Once a suitable energy source and the fiber optics end geometrical form is selected, the problem now becomes one of efficiently coupling the energy from the source to the fiber optics, and then extracting the energy from the fiber and coupling it to a suitable detector. For a gimbal pickoff mechanization, an optical lens interface is proposed. Simple lenses are used between the source and fiber and the fiber and detector to increase the coupling into and out of the fiber. In the source, the standard optical formulas are used to select a lens and to achieve spacing distances that will focus the LED or laser diode radiation on the fiber end with a converging

beam that matches the acceptance angle of the fiber. On the receiving end, the diverging beam of radiation from the fiber is calculated and a suitable lens chosen to collect this energy and completely focus it onto the sensitive area of the detector. Note that losses due to the reflection from the ends of the fibers will still occur.

The difference between the radiation source power level and the power level required at the detector for a given signal-to-noise ratio is termed the *budget*. Elements of this budget are the input coupling losses, fiber attenuation, and output coupling losses. Each of these elements can be estimated and their sum compared to the loss budget to determine link feasibility. A usual conclusion of a link analysis is a value for fiber loss in dB/km for the given distance.

Presently, the fiber optics appear to be on the brink of a technological explosion in the field of communications. Recent breakthroughs in producing low-loss optical fibers are approaching theoretical limits. In military applications, the characteristics of small size, low weight, no emitted radiation, interference immunity, and radiation hardness are important. The replacement of multiple gimbal wires and slip rings with a single fiber bundle is cost savings and actually improves reliability. Optical fibers are completely non-inductive and non-capactive; shielding and filtering are eliminated.

Meanwhile, developments in radiant energy sources, fibers, polarizing beamsplitters, thin film polarizers, and intensity/position sensing detectors are making integrated optical gimbal pickoff concepts look very feasible.

C. POLARIZING BEAMSPLITTERS.

Polarizing cube beamsplitters consist of a pair of identical right-angle prisms, with hypotenuse faces cemented together with a special multilayer of dielectric film vacuum deposited upon one of the hypotenuse faces.

The cube beamsplitter has several specific advantages over flat-plate beamsplitters and is widely used because of these. It deforms less in response to external mechanical stress or inertial load, and most importantly, it is free of ghost images. It gives excellent performance over wide ranges of angles of incidence, is rugged, easy to mount, and ideal for beam superposition applications.

Monochromatic unpolarized radiation, which is orthogonally incident upon the external faces of the cube and internally incident at 45 degrees upon the multilayer, is separated into two polarized beams which emerge from the cube through adjacent faces and in direction which are

accurately 90 degrees apart. The beam which passes straight through the cube emerges plane polarized to a purity of 98 percent or better, with the plane of the electric field vector parallel to the plane of incidence defined for the multilayer film ("p"-polarized). The beam which emerges from the cube at right angles to the incident beam, having been reflected by the multilayer film, is also plane polarized to a purity of 98 percent or better. This time the electric field vector orthogonal to the plane of incidence is defined for the multilayer film ("s" polarized).

For unpolarized monchromatic input at the intended wavelength, and without the use of any retarder, these beamsplitters always achieve a very accurate 1:1 ratio regardless of beamsplitter orientation.

D. THIN FILM OR SHEET TYPE PLANE POLARIZERS

The emergent radiation from the cube beamsplitter is plane-polarized. The polarizing direction is established during the manufacturing process of the cube and the beamsplitter will only transmit "p" polarization and reflect "s" polarization. The maximum amount of radiant energy, that is the intensity, which can be polarized is just half the unpolarized incident energy.

If the incident beam is unpolarized and the angle θ is defined to be the angle between the planes of the preferred "p" polarization of two polarizers (cube polarizer and thin film polarizer) in near contact, it can be shown that the "p" polarization intensity (I) varies with θ according to

$$I = K_1 K_2 \sin^2 \theta + \tfrac{1}{2}(K_1^2 + K_2^2) \operatorname{Cos}^2 \theta . \qquad (3)$$

K_1 and K_2 are the principal transmitters of the polarizers, and both are functions of wavelength. K_1 is always somewhat less than unity, and K_2 always has some small but nonzero value. Therefore, the transmitted "p" polarization intensity of the pair is approximated by:

$$I = I_m \operatorname{Cos}^2 \theta \qquad (4)$$

where I_m is the maximum value of the transmitted "p" polarization intensity when equation 3 equals $1/2(K_1^2 + K_2^2) \cos^2\theta$. This occurs when the polarizing directions of both polarizers axes are parallel. Minimum "p" polarization is transmitted when the two polarizers axes are crossed.

The degree of polarization is virtually independent of the incidence angle. Linear polarizers may be used, therefore, in highly convergent or divergent beams and still produce uniform polarization.

Present technology and fabrication techniques indicate acceptable performance for thin film polarizers.

E. DETECTORS

A detector senses electromagnetic radiation, including laser light, and produces electrical output that is proportional to the optical input. This electrical signal can be measured directly or used to drive electronic circuitry. The development and production of all types of visible and mid-infrared detectors are available. Some are:

- Silicon.
- Gold-antimony doped germanium, n type.
- Lead sulfide.
- Tellurium.

Most commercial semiconductor sources emit at 800 to 900 nm. A significant trend, however, is development of emitters and detectors for 1,200 to 1,300 nm spectrum portion where the attentuation of fused-silica optical fibers is very low. Most manufacturers can tailor detectors to requirements for size, speed of response, optical trimming, noise equivalent power, and packaging.

3. GIMBAL PICKOFF TECHNOLOGICAL MECHANIZATION STUDIES

A. RADIANT ENERGY PICKOFF CONCEPT

A gimbal pickoff concept for wide angle two-degree-of-freedom gyros is proposed using a combination of fiber optics and radiant energy source/defectors for low torque gimbal/housing position information. The mode of operation for the gyro concept is a sustained rotor altitude type instrument.

The pickoff concept can be used on any two-degree-of-freedom gimbal gyro. The advantage of the radiant energy pickoff concept is that it eliminates gimbal wiring torques. The gimbal potentiometer type pickoff and slip ring designs have been problem areas on present gyros such as wiper lift-off during flight environment, noise, increased friction, and assembly cost.

The wide angle gyro concept (*Figure 1*) consists of an inner gimbal frame (1), spin bearing shaft (2) that is attached to the inner gimbal frame, rotor (3) which is decoupled from the shaft through bearings (4), outer gimbal frame (5) which is decoupled from housing (6) through gimbal bearings (7). Inner gimbal frame (1) is decoupled from outer gimbal frame (5) through bearings (9). Reflective/non-reflective pattern (10) is fabricated on rotor (3) external surface. Fiber optics (11), (12) are located concentric through a hole on outer gimbal shaft axis (13) for transmitted/reflected energy paths from energy source to rotor reflective/non-reflective pattern and back to sensor (14). Reference number (15) provides energy source and data processor sensor/electronics for inner gimbal pickoff position sensor. Outer gimbal shaft (16) provides a reflective flat surface (17) for outer gimbal position sense. Reference number (18) provides energy source and data processing sensor/electronics for outer gimbal reflective surface (17) position intelligence. Reference number (20) provides gimbal/housing cage and gas energy for rotor (3) spin-up. Reference number (21) provides stored gas energy for rotor (3) sustain supply. Reference number (22) is an open/shut valve for the sustainer gas bottle. Explosive device (23) is used to activate rotor spin-up and to uncage gimbal from housing (6). The uncage activation opens value (22) thus releasing energy to sustain rotor (3) and automatically closing entrances to spin-up line (20).

The operational cycle of the inertial instrument is described: An activated explosive device (23) energizes rotor (3) to required angular momentum. Exhausted spin-up gas supply retracts gas line (20) thus uncaging gimbal (1) from housing (6). The uncaging action opens valve (22) of sustain bottle (21) and automatically closes spin-up line entrance (20). Gas bottle (21) provides gas energy through gimbal (1) spin-up nozzles to maintain required sustained inertial reference rpm. Missile body motion coupled through housing (6) is sensed by the inertial reference pattern (10) and gimbal shaft reflective surface (17). Radiant energy transmitted from (15) through fiber-optics (11) and reflected from pattern (10) is returned through fiber-optics (12) onto energy sensor/electronics (15). The processed radiant energy data represents a digital form of the inner gimbal angle between the inertial reference (3) and housing (6). Reference number (18) provides transmitted radiant energy onto reflective surface (17) and returns to energy sensor/electronics (18). Processed (18) radiant energy data represents an analog signal of the outer gimbal angle between the stabilized inertial reference surface (17) and housing (6). This concept provides missile body attitude information by utilizing body mounted radiant energy sources and sensors to measure the angle between the inertial reference (3) and missile body (6).

B. THIN FILM PLANE POLARIZED INTENSITY PICKOFF CONCEPT

The thin film plane polarized intensity pickoff concept uses a stabilized plane of polarized radiant energy to measure angular position about a stabilized axis. This gimbal pickoff concept is proposed for low-cost design using optical technology.

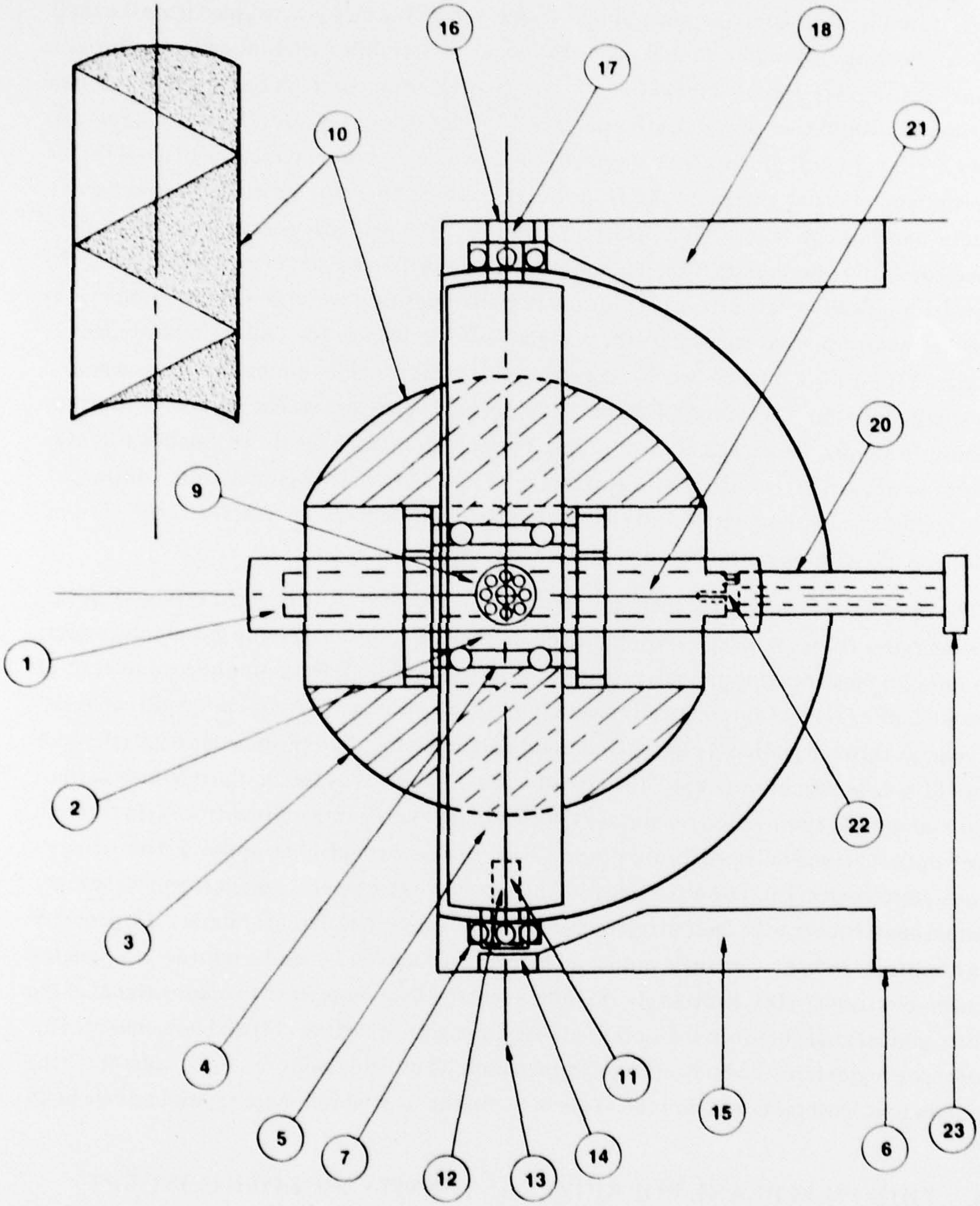


Figure 1. Sketch of the two-degree-of-freedom gyro with radiant energy pickoffs.

The wide-angle thin film plane-polarized pickoff concept (*Figure 2*) consists of a stabilized gimbal (1) which is decoupled from housing (2) through bearings (3). An unpolarized radiant energy source (4) is secured to housing (2). A fiber optic path (5) is mounted on stabilized gimbal (1). A polarizing cube beamsplitter (6) is attached to stabilized gimbal (1). Thin film polarizer (analyzer) (7) and an intensity energy sensor (8) are mounted on housing (2). Sensor (9) is used as a gimbal position direction indicator using the "s" polarization from beamsplitter (6).

The operational cycle of the plane polarized pickoff concept is described in *Figure 2*.

Gimbal (1) stabilization activates radiant energy source (4). The unpolarized energy is transmitted from source (4) through the fiber-optic path (5) to polarizer (6). The radiant energy emerging from polarizer (6) is "p" plane-polarized. The polarizing direction is established during the manufacturing process and assembly. Polarizer (6) will transmit only those wave-train components whose electric vectors vibrate parallel to this direction and will absorb those that vibrate at right angles to this direction. The intensity of the "p" plane-polarized energy transmitted through analyzer (7) varies according to Malus Law. That is, the maximum intensity occurs when the polarizing direction of polarizer (6) and analyzer (7) are parallel. If analyzer (7) is rotated about the direction of energy propagation, there are two positions at which the transmitted energy intensity is almost zero; these are the positions in which the polarizing directions of polarizer (6) and analyzer (7) are at right angles. Therefore, the intensity of the transmitted "p" polarized energy from polarizer (6) through analyzer (7) varies with the angle of rotation according to

$$I = I_m \cos^2 \theta, \qquad (5)$$

in which I_m is the maximum value of the transmitted intensity.

To achieve a linear intensity scalefactor range from null (almost zero intensity) to ±40 degrees, a special designed analyzer (7) is required as shown in *Figure 3*. There exists in analyzer (7) a certain characteristic polarizing direction as shown by the parallel lines in *Figure 3A*. This polarizing direction is established during the manufacturing process by embedding certain long-chain molecules in a flexible sheet and then stretching the sheet so that the molecules are aligned parallel to each other. Plane-polarized energy falling on analyzer (7) will transmit only the parallel electric vector components. Analyzer (7) uses a concept that removes a ±25 degree pie-shape area along the zero intensity axis. *Figure 3B*, analyzer (7) parts are rejoined at the cut-out boundaries. This design allows the null to occur at ±25 degrees from the right angle axis. The transmitted energy intensity at null is now about 18 percent of the maximum intensity transmitted when polarizer (6) and analyzer (7) are parallel.

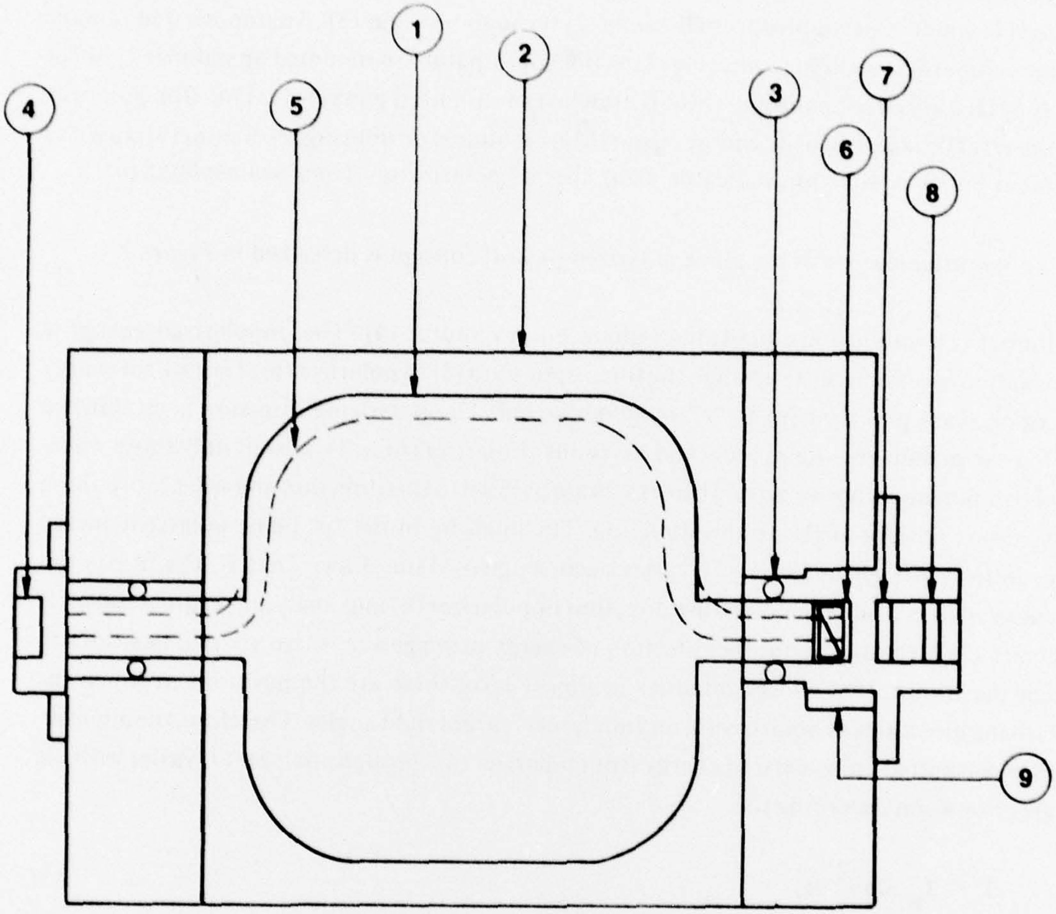


Figure 2. Sketch of the thin film plane-polarized intensity pickoff concept.

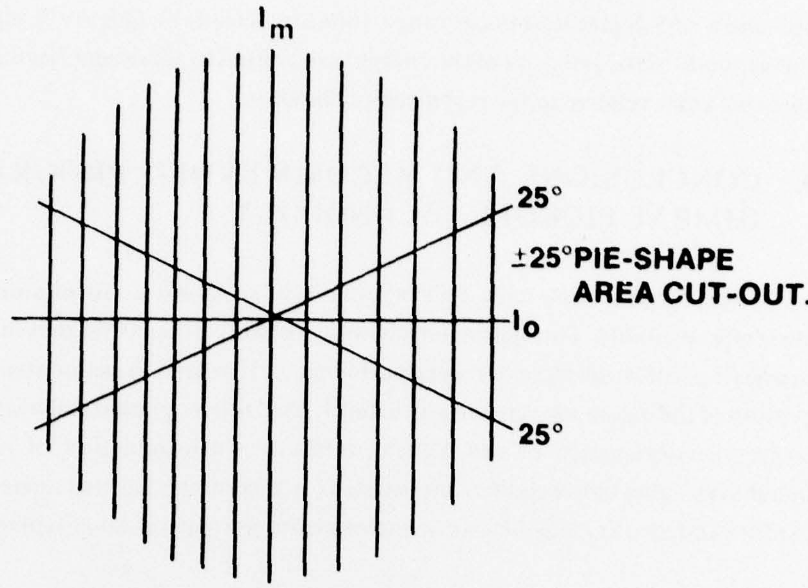
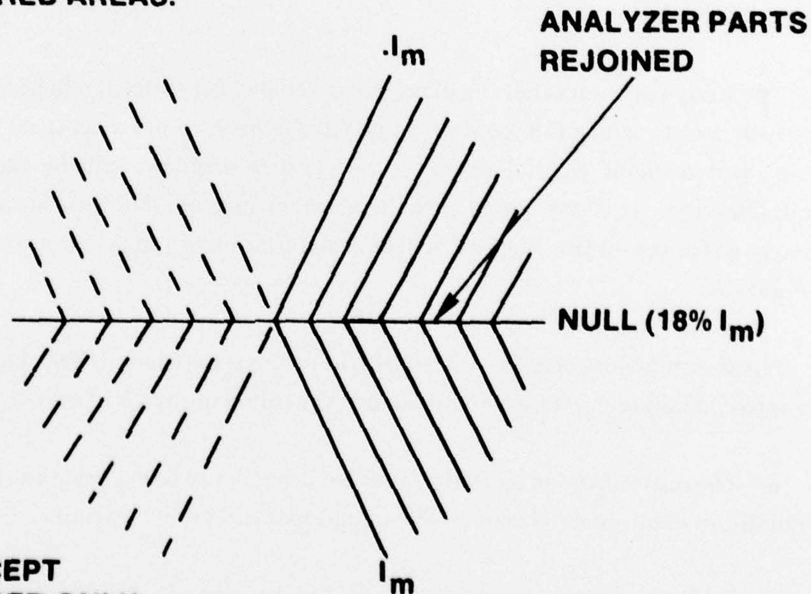


Figure 3A.

OPTION #1 CONCEPT.
ENERGY ABSORBED IN BOTH
BLANK AND DASHED AREAS.



OPTION #2 CONCEPT
ENERGY ABSORBED ONLY
IN THE BLANK AREA.

Figure 3B.

Figure 3. Sketch of analyzer (7) concept.

Figure 4 illustrates the predicted intensity scalefactor covering a ±40 degree linear range from null and a ±65 degree non-linear range. Intensity sensor (8), (*Figure 2*), electrical output signal corresponds to the intensity of the energy transmitted by analyzer (7) which is a function of the analyzer angle relative to the stabilized polarizer (6).

4. CONCLUSIONS AND RECOMMENDED PROGRAM TO PROVE GIMBAL PICKOFF TECHNOLOGY

A decade from now, most ball bearings will look and perform about the same as those currently available. Though materials will probably differ from present analyses, improved processing will be developed to keep performance the same. A major assumption is that a good portion of the metal-alloy materials currently used in gyro gimbal and bearing housings may fall under the dominance of new developments in the production of new plastics, powder metallurgy, and lightweight composites. It is recommended that these areas be studied, to explore and identify feasible exotic materials for gyro metal-alloy replacements.

Meanwhile, the gimbal pickoff analysis concludes and recommends that the concept using the pulse duration modulation pickoff design proposed in *Figure 1* be developed as an inner gimbal wide angle position sensor. For the outer gimbal, it is recommended that the thin film plane polarized intensity pickoff concept proposed in *Figure 2* be developed as a wide angle position sensor.

The study concludes that the plane polarized pickoff concept will be less expensive than the curved surface sensor (18) concept shown in *Figure 1*. In practice, sheet resistance is probably the most difficult characteristic to control and probably will be the dominant cause of nonlinearities. It is concluded that the sheet surface control for a small flat surface such as required for sensor (8), *Figure 2*, will be easier to control and lower in cost than for sensor (18), *Figure 1*.

It is recommended that the next step in the progression toward a feasible demonstration of the gimbal pickoff technology should include the following areas of investigation:

- The recommended gimbal pickoff concept should be designed and fabricated to interface radiation/fiber optics/sensor to show demonstration of its feasibility, performance, and cost.

- Radiation/fiber optics/sensor should be optimized for maximum power transfer, performance, and low cost.

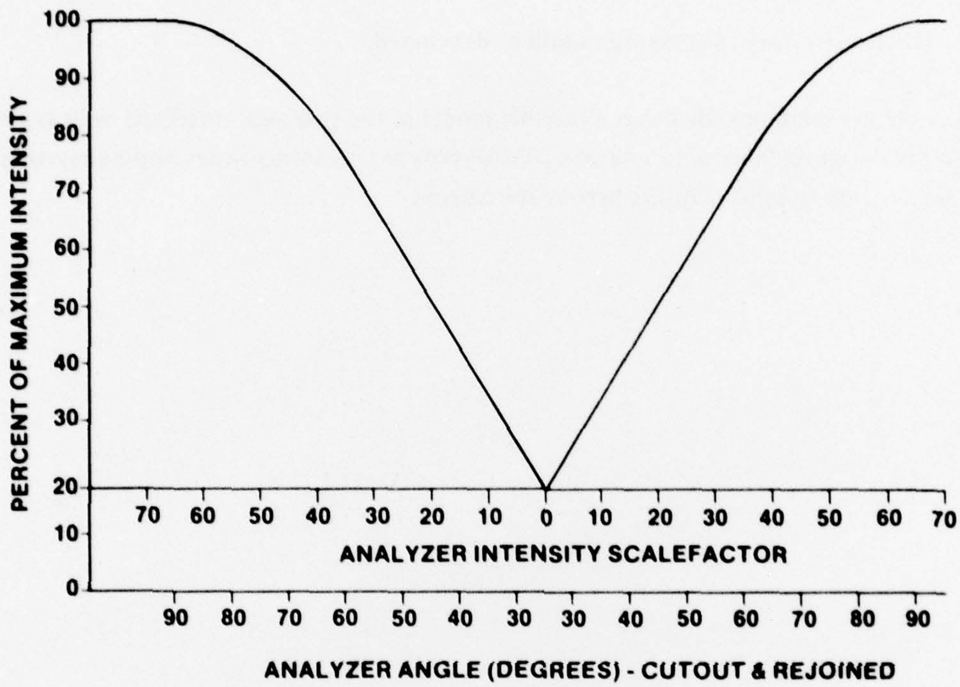


Figure 4. Predicted analyzer intensity scalefactor.

- Verify pickoff performance in operating and storage environments.

- Hybrid electronic packaging should be developed.

It is further recommended that a feasible model of the two axes stabilized optical gimbal pickoff be designed, fabricated, and analyzed to verify its technology in developing a system into practical reality to achieve future gyro requirements.

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